LARGER MODULES, FINER DETAILS

Kaveh Ebrahimi and Daniel Inglis, Fluor Ltd, UK, set out design considerations for pressure vessels during seaborne shipment in modules.

Modularisation of process plants is an execution approach for design, procurement and construction that moves the majority of construction effort away from site. Large modules are primarily steel structures containing process equipment, machinery, electrical and instrumentation items and pre-assembled units (PAUs).

Modular construction involves building all or part of a facility's units in one or more off-site locations and then transporting the units to the jobsite for installation and erection.

A 'module' can be defined as a transportable pre-assembly of process plant components (structural steel, piping, equipment, instrumentation, electrical, etc.) designed to minimise site installation and commissioning labour costs.

Traditional 'stick-built' construction is performed at site with no modularisation, but generally with steel and pipe fabricated off-site.

Some of the dominating factors in making the decision to shift the construction effort from site to a controlled workshop environment by using a modular approach include the following:

- Remote site access.
- Severe site weather conditions.
- Limited availability of regional skilled labour.
- Poor regional security.
- Schedule-driven execution.

The module assembly and shipping execution plan must be known by the project team during the early stages of the project.

Large modules can weigh more than 500 t, requiring careful planning and engineering to address unique design issues when compared to stick-built construction.

For instance, where restrictions exist during land, sea or river transportations, a module containing vertical vessels may need to be assembled horizontally on its side in the modularisation yard, equipment inserted, shipped to the construction site, and then erected as an entire module in a vertical position. In this situation, it is essential that the horizontal shipping execution plan be known by the mechanical, structural, piping engineers, and the equipment supplier. This scenario is not encountered in conventional stick-built design and construction.

Engineers need to identify and account for all of the shipping dynamic loads which may require additional temporary shipping steel, reinforcement of vessels or their supports, special shipping saddles for vertical vessels, or special temporary brackets.

Forces resulting from transportation acceleration on modules must be analysed based on the specific sea route taken and the particular ship characteristics. Similar transportation accelerations will be developed during the heavy haul and land phase lift and transport of modules.

There are various advantages for using modularisation for construction instead of a traditional stick-built approach. A few of the advantages are listed in Table 1.

However, with a change from a stick-built approach to a modularisation approach for construction of process plants, there are challenges that need to be addressed early on in the project. Some of the challenges of using a modularisation approach are listed in Table 2.

Types of modules

Various types of modules can be utilised for construction of process plants. Some of the most commonly used type of modules are listed here:

- Pre-assemblies.
- Small or truckable modules – transported by road or rail to landlocked locations (shipping envelope limitations).
- Large modules – weighing between 100 – 600 t (conventional rigging).
- Very large modules – weighing more than 600 t (non-conventional rigging and transportation).
- Offshore modules – offshore facilities.
- Barge-mounted modules – entire plant built on barge(s).

Table 1. Advantages of modularisation of process plants

Reduction in total installed cost and overall plant cost
Reduction of on-site craft labour
Achieving higher labour productivity for shop or modularisation yard
Increasing the amount of work performed at ground level
Construction schedule optimisation
Improving quality and safety of work

Table 2. Challenges of modularisation of process plants

Increased complexity of engineering
Increased steel quantities and complexity for design of steel structure
Increased complexity of road and sea transportation
Limitation on the size and weight of equipment
Additional interface between engineering and procurement departments with modularisation yard
Increased complexity of activity planning and scheduling: accelerated review of vendor data and equipment delivery
Difficult pipe routing, potentially creating higher nozzle loads
Implementation of Human Factors Engineering issues due to tight available space

Successful transportation of modules

It is the responsibility of the engineering contractor to design the modules correctly for safe transportation from yard to site and installation.

All types of supports can be used for pressure vessels inside modules, i.e. saddles for horizontal vessels or lugs, legs or skirts for vertical vessels.

There are several unique issues that should be addressed for the design of pressure vessels and their supports in a modular construction:

- The correct design of pressure vessel supports may be governed by structural steel layout of the module, therefore this needs to be carefully checked during the development of the project and constantly communicated to the pressure vessel vendors.
- For pressure vessels being manufactured for conventional stick-built construction, they are usually built within a set of specified project tolerances and these tolerances assume a standard grouting under the base plates of pressure vessel supports. However, in a modularised construction, it may be beneficial to apply tighter tolerances to module items, in order to avoid excessive shimming and to ensure a suitable contact area between the base plates and module steelwork.
- Custom designed temporary supports (i.e. lugs, guides/bumpers, etc.) may be required for pressure vessels during transportation inside modules.
  - It is beneficial to use single base plates (with or without gussets) over chairs or double rings.
  - Allowable stress of structural bolts and the maximum bolt size and length that can be utilised should be checked with the structural engineering team to ensure that unrealistic assumptions are not made.
  - Pressure vessels and their supports should be designed for motions and accelerations specified in the transportation specification after a careful review of the route(s) that the modules might take from fabrication yard to site.
  - Piping transport reactions at nozzles shall be considered, particularly for thin wall pressure vessels. Vessel and steel structure deflections need to be accounted for when piping reactions at nozzles during module transportation are calculated; results shall be compared against the piping load values determined for the operating case. The option of adding temporary pipe supports and guides should also be explored.
  - The design of equipment modules for sea or land transportation requires a joint effort involving multiple disciplines from the early stages of the project. There should be a continuous exchange of information between mechanical, structural and piping design teams regarding the vessel weight,

Table 3. **Sample accelerations during transportation of modules**

Transportation mode	Vertical load		Lateral load	Longitudinal load
	Downward	Upward		
Truck (motorway speeds)	1.7 g	0.5 g	0.3 g	1.8 g
Truck (non-motorway speed/ multi-wheel transporter)	1.3 g	0.2 g	0.2 g	0.2 g
Rail	2 g	2 g	2 g	3 g
Oceangoing ship or barge	2 g	2 g	0.75 g	0.4 g

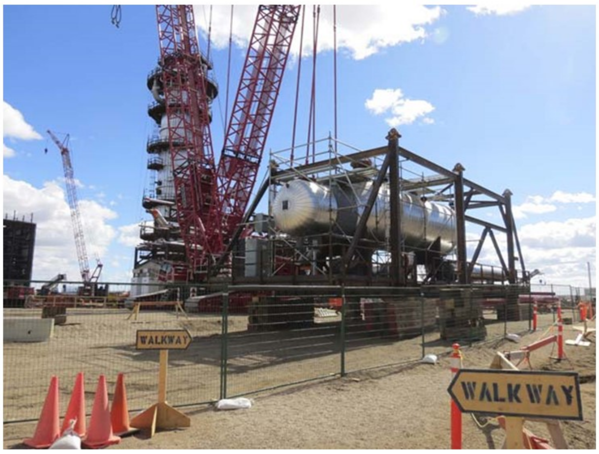

Figure 1. Small horizontal pressure vessel in module (Shell Quest Carbon Capture and Storage Project).

support configuration, base loads, additional support point reactions and piping loads as the module and vessel design may require several iterations. It is not always possible to brace the vessels to the steel structure if the structure deflects more than the vessel during transportation; for vertical vessels that cannot be braced, the transportation loads will likely govern the vessel support design.

- Location of nozzles or temporary support lugs may be restricted by location of major steel beams.
- Trays inside columns are usually installed at the pressure vessel fabrication shop or modularisation yard, and they need to be designed for all transportation loads, including for horizontal transportation of vertical columns. It may not be possible to install some internals for shipment (e.g. column packing), for fear of it becoming damaged during transport. It may therefore be necessary to install such items at site. Additionally, trayed columns will need to be inspected on arrival at site, to ensure that the trays have not been damaged or have displaced during transport. Such works need to be identified in advance in a 'carryover work plan', and shared with the project site team.
- Structural bolts on sliding saddles are not usually considered to be load-taking during transportation of modules.
- A set of pre-loads should be identified for structural bolts, to ensure that they stay in tension during all transportation scenarios.
- During road transportation there may be a need to raise high voltage powerlines as necessary to meet the overhead clearances required by the local regulations.
- Restrictions at site may also influence module design requirements (overhead piperacks, for example).
- Design of pressure vessels in modules must consider the load combinations of ocean transportation and wind; acceleration factors increase with elevation relative to the ship's centre of buoyancy.

Table 3 shows a sample of transportation loads to be applied for design of pressure vessels in modules. Note that high acceleration loads during seaborne shipment can have a significant effect on the design and adequacy of transportation saddles or brackets. Also, vessel elevation relative to the module base shall be considered.

Horizontal pressure vessels in modules

Horizontal pressure vessels in modules are usually supported on saddles. Whilst for transportation of large horizontal pressure vessels for stick-built construction the vendor may provide extra temporary saddles that can be later removed at site prior to final transportation, for horizontal vessels in modules it is usually not feasible to use temporary saddles due to space and weight limitations of the modules, and therefore the permanent saddles need to be designed for loads resulting from ship movements during ocean transportation. To this end, the designer needs to carefully review the loads applied on the equipment during seaborne shipment and provide a safe design by making sure the saddles have enough strength or are further reinforced by addition of steel bracing. There may be a need to use temporary steel bracing to fix the saddles to the supporting beams. These temporary bracings may need to be removed later at site. Figure 1 shows a typical horizontal pressure vessel in module.

It is beneficial to remember that if the structural bolts on sliding saddles are tightened for ocean transport they need to be marked and loosened once the module is installed at site. In any case, structural bolts on sliding saddles cannot be assumed to take any longitudinal loads during transportation of modules because the sliding support cannot be fixed in the longitudinal direction. This requires that the fixed saddle resists all the longitudinal transport loads. Alternatively, shear stops can be used at the sliding saddle to resist longitudinal loads, but these shear stops have to be removed at site requiring further site coordination.

Short vertical pressure vessels in single horizontal modules

Short vertical pressure vessels may be shipped in their operating positions in a fully-contained single horizontal module. Short vertical pressure vessels can be usually designed fairly easily with regards to transportation loads, and if necessary can be braced to the single horizontal module. Simple small vertical pressure vessels (in blue) in a horizontal module are shown in Figure 2.

Long vertical pressure vessels in multi-level horizontal modules

Long vertical pressure vessels can span several horizontal modules in a multi-level horizontal module structure.

Depending on their size and weight, and the ocean transportation route taken (and resulting acceleration forces), such vessels may be installed in the lower module at the modularisation yard or may be shipped separately to site and then installed inside the modules. If installed for transport, additional support guide(s) will likely be required further up the vessel.

Vertical pressure vessels in vertical modules

Vertical pressure vessels in smaller vertical modules may be shipped in horizontal position to site and therefore need careful design and engineering with regards to transportation loads. Extra support lugs can be added to the vessel at locations coinciding with module floors as shown in Figure 3. Once the equipment is shipped and erected in position at site, the extra lugs should be unbolted from the surrounding steel structure.

Long vertical pressure vessels that extend beyond the height of the top floor of the module will need to be reviewed to identify the requirements for additional supports.

Figure 4 shows a typical support lug for fixing the equipment to the surrounding steel structure during transportation. Once the equipment is installed, the support must be unbolted from the module structure.

Fatigue assessment of modules for ocean transportation: a brief guideline

A transport fatigue assessment is not generally required for pressure vessels, as long as the equipment is adequately supported. There is no evidence to suggest that vessels shipped within modules are more susceptible to fatigue damage compared to those shipped loose. However, this is not the case for the module structure itself. When the voyage duration exceeds 10 days, it is recommended that a transport fatigue analysis is performed, using sea-state design data obtained for the time of year and duration of the voyage. This is of greater importance when the structure is also subject to in-service fatigue, the principle source of which is likely to be from rotating equipment.

Conclusion

Whilst modularisation of process plants is becoming increasingly popular for the construction of new facilities, decisions must be made as to when they are effective, as there are numerous challenges that need to be addressed when designing equipment for modular construction.

This article has tried to provide some guidance regarding the numerous challenges and the possible solutions for design issues related to ocean transport of pressure vessels in modules.

Bibliography

1. MCBRYDE, R. D. and LUPINSKI, M., 'Modularization with Mechanical Equipment', Chemical Industry Digest, (November 2012).
2. BOS, A. J., and LIGTERINK, T. M., 'Influence of Ocean Transport on the Design of Onshore And Offshore Constructions, Modules, Topsides, Jackets And Towage On FPSO Design', Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering.
3. LIU, Z., et al., 'Module And Vessel Interaction Analysis for Module Ocean Transportation', Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering.

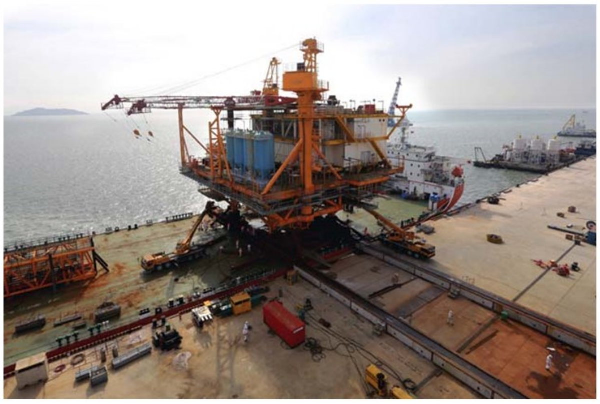

Figure 2. Short vertical pressure vessel in single horizontal module.

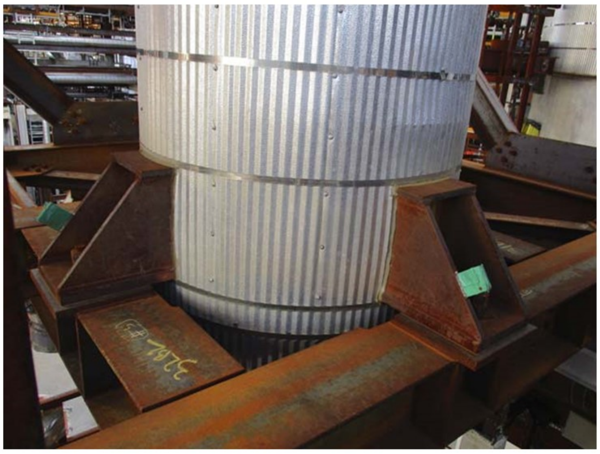

Figure 3. Extra lugs for vertical pressure vessels.

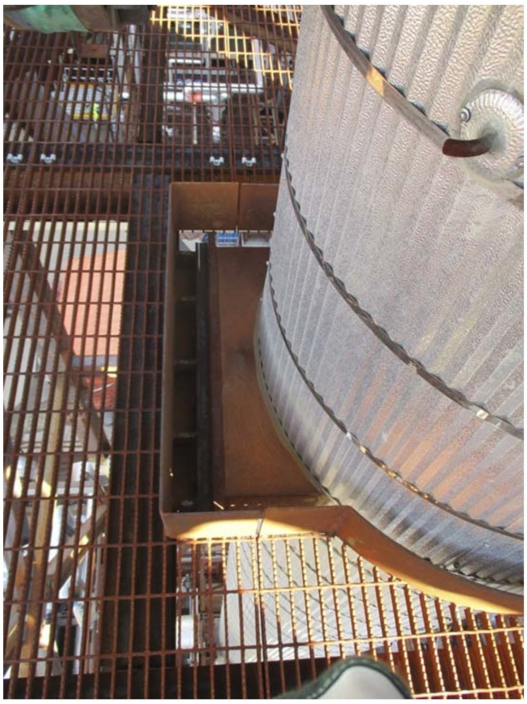

Figure 4. Additional support for horizontal transportation of large vertical pressure vessel.